# Validating Greenhouse Gas Flux Estimates from Agroecosystems

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Although $CO_2$, $CH_4$ and $N_2O$ fluxes have been measured for over 30 years, our knowledge of the sources and sinks of these greenhouse gases (GHG) is still very limited. Many measurements have been conducted on small plots or individual animals using various sizes of enclosures leading to abundant detailed information on small-scale processes being obtained. The level of knowledge on GHG emissions at larger scales, however, is highly uncertain because of the difficulties associated with extrapolation in space and time. As a result, national and global GHG flux estimates are more uncertain. Our inability to balance the global C cycle demonstrates the uncertainty of present carbon emission estimates (Figure 1). Scientists have been unable to account for 1.8 of the 7.1 Pg of $CO_2$-C per year released by human activities (Kaiser and Schmidt, 1998). Similar uncertainties exist for the flux estimates of $CH_4$ and $N_2O$. Methane sink estimates of 515 Tg $y^{-1}$ imply sources totalling 552 Tg $y^{-1}$, while only 535 Tg $y^{1}$ have been identified so far (Prather *et al.*, 1995). This discrepancy implies that sources are underestimated or unknown. Similarly, globally identified $N_2O$ sources are 14.7 Tg N $y^{-1}$ while the implied sources should be 16.2 Tg N $y^{-1}$, based on sinks of 12.3 Tg N $y^{-1}$.

Globally, agriculture is responsible for approximately 25% of the $CO_2$, 50% of the $CH_4$ and 70% of the $N_2O$ emissions released by human activities. In Canada, we estimated that in 1996, agroecosystems contributed 13% of the total anthropogenic emissions. That is 7% of the $CO_2$, 33% of the $CH_4$, and 60% of the $N_2O$ (Janzen *et al.*, 1998). Although the total contribution is rather small, it is important because agroecosystems are intensively managed and the emissions might be controllable without creating serious difficulties to agricultural producers.

This paper briefly describes the measurement techniques used to determine the fluxes of GHG emanating from soil, plant and animal sources in agroecosystems . Advantages and limitations of various techniques are discussed in the context of spatial and temporal scales. Approaches for extrapolating results, and validating larger scale GHG estimates are presented.

## Measurement Techniques

Techniques and platforms for measuring GHG fluxes need to be selected in accordance with the goal of the study. Important criteria for selecting the appropriate measurement technique include the spatial and temporal coverage required, and the expected magnitude and variation of the fluxes.

*Studies on soil and plants*

Tables 1a and 1b (adapted from Topp and Pattey, 1997) present the most commonly used or promising techniques with the spatial and temporal scales that they cover and some of their relative advantages and drawbacks. Soil core incubation or soil vertical probes are mainly used for studying GHG production rates rather than atmospheric emissions. Close-chamber techniques measure GHG fluxes by isolating a soil area or a plant from the atmosphere, and measuring the change in GHG concentration over time (Mosier, 1989; Rochette, *et al.*, 1997). The concentration analysis is usually done on site for $CO_2$ and in the laboratory with a gas chromatograph for $N_2O$ and $CH_4$. Very small fluxes can be detected using the closed chamber technique by reducing the chamber height or increasing the sampling period. Open-chambers are rarely used for measuring soil fluxes because they require a much more sophisticated set up, including the analysis in real-time of GHG concentration difference between the inlet and outlet of the chamber; the resulting flux is proportional to this difference. The main advantage of open-chambers is the possibility to control ambient conditions such as GHG concentration, humidity, and temperature. Both open and closed chambers require a lot of measurements in order to account for soil heterogeneity and short-term variations.

Eddy flux techniques offer several advantages over chamber techniques. The most important advantage is the ability to integrate the GHG fluxes over much larger areas and on a continuous basis for tower-based systems. Furthermore, measurements are taken in situ without interfering significantly with the studied environment. However, the detection limit of the GHG analysers needs to be much higher than for chamber techniques. Businger and Delany (1990) give a full description of the trace gas sensor resolution required for measuring trace gas fluxes by the eddy-covariance, relaxed eddy-accumulation and gradient techniques. The gradient technique is the traditional way of measuring fluxes with slow-response sensors and is still frequently used for methane and nitrous oxide. Using this technique, the flux is proportional to the mean vertical concentration gradient of the gas multiplied by an eddy diffusivity coefficient. Precautions need to be taken to ensure that sampling levels are at the correct height above the surface in order to ensure the validity of the approach (Cellier and Brunet, 1992).

Among the eddy flux techniques, the eddy-covariance method is the most direct approach used to measure surface fluxes. It requires fast-response sensors, having a response time of about 0.1s, to measure the fluctuations of the vertical wind velocity and GHG concentration which are then averaged over time for tower-based systems, and over space for aircraft-based systems. A comprehensive description of the theoretical basis and the experimental limitations of these techniques can be found in several references (Businger 1986; Baldocchi *et al.* 1988; Desjardins *et al.* 1993). When no fast-response sensors are available, the relaxed eddy-accumulation (REA) technique offers a good alternative. REA has a similar theoretical basis to the eddy-covariance technique (Pattey, 1996). Air is sampled using fast-response valves in two distinct reservoirs conditionally to the vertical wind velocity (updraft or downdraft). The resulting flux is then proportional to the difference in GHG concentration between the upward and downward moving air cumulated over a given time period. The difference in concentration between updraft and downdraft samples is usually very small (Desjardins *et al.* 1993) requiring instrumentation capable of making high-resolution measurements; for methane, a concentration difference of 1 ppbv is equivalent to a flux about 10 mg $m^{-2}$ $d^{-1}$.

Fast-response tunable diode lasers are now available for measuring methane and nitrous oxide (Ogram *et al.*, 1988). With such tunable diode lasers, the required high-resolution measurements can be obtained. For example, the tunable diode laser provides high-resolution methane gradient measurements of 0.1 ppbv root mean square error based on a 30-minute sampling period. However, because of their weight and sensitivity to vibrations, tunable diode lasers are not suitable for aircraft-

based flux measurements. The best alternative to eddy-covariance for an aircraft-based platform is to use the REA technique for sampling and to analyse afterwards the air samples using either a ground-based tunable diode laser or gas chromatograph (Zhu *et al*, 1998).

*Studies on livestock and manure*

Enteric fermentation contributes about 80% of the $CH_4$ emissions from agroecosystems in Canada. Two types of enclosures have been used. Individual animals have been placed in a small chamber and emissions measured as a function of diet etc. (McAllister *et al.*, 1996). An entire dairy barn has also recently been instrumented and used as an enclosure, allowing the herd to stay in its natural environment. The diurnal GHG emission cycle was monitored using infrared $CO_2$ and $CH_4$ analyzers (Kinsman *et al.*, 1996).

Scientists have also measured $CH_4$ produced by animals in the field and in feedlots using sulfur hexafluoride ($SF_6$) as a tracer gas. Tubes that gradually release $SF_6$ at a constant rate are placed in the animals' rumen. Then, by comparing the ratio of the concentrations of $CH_4$ and $SF_6$ expired by the animal, the researchers can calculate the $CH_4$ produced. $SF_6$ has also been used as a tracer gas in the atmosphere to calculate $CH_4$ downwind of feedlots and manure storage tanks (Figure 2) (Kaharabata, 1998). Denmead *et al.*, (1998) recently used the mass balance method to measure the production of $CH_4$ and $N_2O$ from a group of animals in a test plot (Figure 3). Methane production was measured for 7 of the sheep simultaneously using both $SF_6$ and the mass balance approach; very similar results were obtained. During this experiment, high $N_2O$ emissions were observed following a rain. Monitoring indicated that substantial $N_2O$ emissions continued several days after the sheep were removed from the test plot indicating the need to integrate emissions over long period of time.

*Temporal and spatial coverage of measurement platforms*

Figure 4 illustrates the temporal and spatial features of the major components of agroecosytems and similarly of the atmospheric systems that interact with them (Cihlar *et al.*,1993). The spatial and temporal scales increase logarithmically from the soil/plant to the biome level. Each agricultural component is nested in the next one, from small to large areas. Figure 5 shows the spatial and temporal scales covered by various measurement platforms. Each technique is restricted in its applicability and therefore, obtaining fluxes at large scales for a long time period is difficult.

Chamber or enclosure techniques provide detailed information about GHG exchange processes on soil, plants (<1 m) or individual animals, but the information is limited in both time and space. Flux measurements using small towers provide information at the field scale on an hourly basis almost continuously for seasons or years, but are somewhat limited in spatial coverage, as equipment is costly and not easily moved. Tethered blimps can be used at discrete time intervals for integrating at the farm scale. Aircraft-based flux systems provide our most promising approach to scale-up flux measurements to the biome level; the scale at which most of our GHG emission estimates are available.

Tethered blimps can be used to monitor vertical GHG profiles up to 200 m in the boundary layer (Figure 6) and the potential exists to use them for measuring fluxes at the farm scale. The convective boundary layer, which develops during daytime up to ~1000 m, is considered to be an integrator of surface fluxes along the path of a column of air moving over the landscape. The average surface flux is calculated from the GHG concentration in and above the well-mixed layer and the convective boundary layer height. It is possible to monitor the build-up of GHG in the nocturnal boundary layer, which is very stable and shallow (~100 m), and to compute the flux by integrating the GHG concentration difference through time over this height (Pattey *et al.*, 1998).

Towers equipped with sonic anemometers and fast-response gas sensors provide gas fluxes at the field- to the farm-scale for periods ranging from hours to years. Approximately 70 towers are presently instrumented worldwide for measuring GHG fluxes continuously (Figure 7). This network is used to quantify GHG fluxes from a wide range of ecosystems in order to account for climate variability in the annual GHG balance. Fluxnet, a worldwide project funded by NASA, was established to develop an infrastructure for guiding, collecting and arranging long-term measurements of $CO_2$ from various ecosystems such as tundra, cropland and old-growth forest. Data from the towers (Goulden *et al.*, 1996) are used to monitor the net $CO_2$ exchange of the terrestrial biosphere. These data are pooled and posted onto the Internet allowing researchers to use them in conjunction with data from inventories, satellites and airborne studies. Various regional networks such as Ameriflux, Euroflux and Japanflux comprise Fluxnet. Ameriflux, for example, which consists of 24 flux towers throughout North America, will measure $CO_2$ fluxes for at least the next 3 years.

Aircraft-based measurements provide a rapid method for measuring GHG fluxes over large areas and provide spatial averages comparable in scale to satellite observations. They have been successfully used to test the representativeness of tower-based observations (Desjardins *et al.*, 1997), and should be particularly useful for validating regional model estimates at an instant in time. Aircraft-based measurements have been an important component of several large-scale studies to quantify the GHG exchange processes for important ecosystems such as the grasslands in Kansas, the boreal forest in western Canada and the wetlands near James Bay.

Satellites provide data of reflectance in various wavebands (visible and NIR, solar radiation, photosynthetically active radiation, etc). From these data, information on land use, vegetation type, leaf area index, surface temperature etc. can be derived.

**Testing GHG models**

Flux measurements from cores, soil profiles and enclosures are helpful for understanding processes. They are frequently used to develop GHG exchange models. Measurements using these techniques cannot be used directly at a larger scale without introducing considerable uncertainties, however, under certain circumstances such as measuring soil respiration during the whole growing season, enclosures are the only way of quantifying GHG fluxes. Process-based models should allow the estimation of GHG emissions at the field scale appropriate for typical crop rotation and management practices.

CENTURY and DNDC (*Denitrification-Decomposition*) models are frequently used to calculate large-scale estimates of GHG emissions in agroecosystems. They provide site specific estimates on a monthly or daily basis and can be run for several years. The spatial coverage for the national estimates is obtained by aggregating these simulations performed under typical environmental conditions and management practices (e.g., Smith et al., 1997). The CENTURY model was developed to determine the effect of crop management and climate change on the productivity and sustainability of agroecosystems. Agricultural management techniques include crop rotations, tillage practices, fertilization, irrigation, grazing, and harvest methods. The model simulates the long-term processes of Carbon, Nitrogen, Phosphorus, and Sulphur for various ecosystems, such as grassland, agricultural crops, forests and savannahs. The model runs on a monthly cycle and contains various submodels, such as the *Soil Organic Matter* submodel, several plant production

submodels, and nitrogen, phosphorus, and sulphur submodels. It requires the following input variables (Parton *et al.*, 1992): monthly average maximum and minimum temperature, monthly precipitation, lignin content of plant material, plant N, P, and S content, soil texture, atmospheric and soil N inputs, initial soil C, N, P, and S levels.

The DNDC Model is a general model of carbon and nitrogen biogeochemistry for agricultural ecosystems. Soil C and N processes are very sensitive to climate, soil properties, and cropping, and therefore, these variables are used as inputs in the model. Cropping practices such as tillage, fertilization, irrigation, manure application, weeding, and flooding are all integrated into the model. The model contains four submodels. The soil climate submodel studies physical soil properties, air temperature and precipitation to determine temperature and moisture profiles through time. This data is fed to the denitrification submodel, the decomposition submodel, and/or the plant growth submodel. The denitrification submodel predicts hourly denitrification rates and $N_2O$ and $N_2$ production. The decomposition submodel calculates daily decomposition, nitrification, ammonia volatilization processes, and $CO_2$ production. The plant growth submodel calculates daily root respiration, water and N uptake by plants, and plant leaf area index (Li, 1998). It can run using daily or monthly climate input data.

More comprehensive process-based models exist such as ECOSYS which require hourly surface boundary conditions for solar radiation, air temperature, humidity, wind speed and precipitation and an extensive description of the environment (site, soil, management practices, crop, atmosphere etc.) (Grant, 1997). The model estimates many variables on an hourly or daily basis such as soil temperature, soil water content, the crop biomass partitioned in the different plant organs, yield, surface energy, and $N_2O$, $CH_4$ and $CO_2$ fluxes. It provides output either at the field or landscape scale that can be used, once validated, to compare the coarser model output or to compute emission factors for the main management practices.

Model outputs need to be verified with independent data sets. Tower-based measurements are most suited for seasonal and annual estimates at the field scale. Validation of models such as CENTURY, DNDC or ECOSYS is being carried out for $N_2O$ and $CO_2$ fluxes after fertilizer application, during winter at snowmelt (Grant and Pattey, 1998) and in the spring (Smith *et al.*, 1998). More validation is required to increase the range of application of these models. Field experiments, designed for validating models require the determination of many ancillary variables such as soil temperature and soil moisture, soil texture structure and fertility, weather data, crop biomass, leaf area index, and a description of management practices. Because the number of field experiments is limited, these experiments should reflect both typical and contrasting management practices for the various ecozones in order to increase the confidence in the models. The process-based models can be run for the typical conditions in order to obtain emissions factors to be included in an IPCC-type methodology for calculating GHG national estimates. Here, mass balance and tracer techniques are particularly useful for validating emission factors. Computing regional and national GHG estimates from inventories and performing sensitivity analyses are also required for determining the field experiments needed to improve the emission estimates.

The fundamental purpose of obtaining flux measurements is to understand and formulate the processes that control the flux, and therefore any model must also incorporate these processes in order to provide accurate regional estimates. All area average models must include: a) a description of surface sources and sinks; b) a parameterization of turbulent transfer in micrometeorological terms; and c) a combination of these concepts in terms of some integrating model.

## Validating flux estimates

The uncertainty associated with global emission estimates is related to the uncertainty of individual flux data sets. The spatial variability of emission rates is often large. It should not be assumed that flux data follow a normal distribution or that the arithmetic average of flux data obtained at a small scale is necessarily the appropriate method for developing regional or national estimates. Several field experiments have shown that certain fluxes (such as $N_2O$) are episodic, and that land use, soil texture and water status strongly influence the emissions.

There is a basic need to minimize errors associated with measurements, as well as to verify the large-scale flux estimates produced by various extrapolation schemes. Remote sensing should eventually be an important source of data to drive the models that are developed to compute emission rates. It is generally agreed that large-scale studies conducted over target areas of special interest are likely to become increasingly important for reducing the uncertainties.

Three types of field studies need to be considered. First, there are intensive studies of specific processes, intended to derive the formulations to be used in process models. Second, there are technique comparison studies, by which confidence is generated in the ability to measure fluxes under field conditions. Third, there are field tests of model predictions. These three types of studies need to be considered in the context of extrapolation from localized chamber studies to areas addressed directly by tower-based measurements to larger areas covered by aircraft-based flux measurements.

For technique comparison studies, one can test the ability to measure fluxes by comparing results obtained over various scales. This frequently involves combining numerous samples obtained over small scales to arrive at an estimate appropriate for the larger scale addressed directly by another method. For example, the result derived from an array of chamber measurements over bare soil can be tested against tower-based eddy flux measurements (Rochette *et al.*, 1997). Evaluating nighttime fluxes measured in the field using eddy flux towers under windy conditions and comparing them with a boundary-layer budget under calm conditions that integrates fluxes over a wider area is another example (Pattey *et al.*, 1998). Selecting a relatively homogeneous area with a minimum size of about 4 $km^2$ and comparing airborne flux measurements against ground-based measurements is a further method of comparison (Desjardins *et al.*, 1997).

Once measurement techniques have been tested, it becomes meaningful to use data collected at coarser scales as independent data sets against which to test model estimates of flux. For example, aircraft-based measurements of fluxes on a scale of 100 km can be used to test scaling-up models that predict the distribution and quantity of fluxes as a function of vegetation and soil characteristics, climatic variables, or other variables obtained through remote sensing. By combining vegetation cover type obtained from remote sensing with aircraft and tower fluxes, an inverting technique has recently been used to solve a linear set of equations for estimating the contribution of each cover type in a given region (Chen *et al.*, 1998). Such models can then be used with some confidence in areas where aircraft sampling is not possible. Other methods for evaluating area-averaged emission rates are available, such as budget calculations over some area containing an emission source of special interest. These methods, however, are less direct than aircraft eddy flux methods and have yet to be fully tested.

**Summary and recommendations**

We have briefly reviewed our capability to measure and model GHG emissions from agroecosystems. In order to help Canada meet its Kyoto commitment, we need to improve our capability to estimate GHG emissions. We also need an elaborate validating scheme that can be used over a wide range of scales. Our recommendations are as follows:

1) Quantify emission factors for a wide range of management practices using techniques such as enclosures, mass balance, tracer gas, eddy flux, etc...
2) Validate hourly and daily model estimates of GHG emissions using tower-based measurements.
3) Scale-up GHG fluxes to the farm scale and develop techniques to validate the estimates.
4) Validate regional estimates of GHG emissions using aircraft-based measurements.

All of these require a co-ordinated effort both within and between ecozones. Performing intensive field experiments using a nested approach covering field, farm and regional scales with different platforms under typical environmental conditions and management practices will permit to improve our understanding of scaling up processes and should result in increased confidence in larger scale estimates.

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**Tables (adapted from Topp and Pattey, 1997)**

Table 1a: Comparison of measuring techniques to determine GHG flux: a) small-scale measuring systems.

| Measuring technique | Time | Space | Analyser | Advantage | Disadvantage |
|---|---|---|---|---|---|
| Core incubation | several weeks<br>Point measurements | <0.01 $m^2$ | $CH_4$ &$CO_2$: GC-FID[z]<br>$N_2O$: GC-ECD[z] | inexpensive<br>controlled condition studies<br>cumulative measurement | no spatial integration<br>Disturbed environment<br>No diurnal cycle |
| soil vertical probe | several weeks<br>Point measurements | <1 $m^2$ | $CH_4$ &$CO_2$: GC-FID,<br>slow-response IRGA[y]<br>$N_2O$: GC-ECD | GHG exchange with depth | soil diffusivity required<br>initial soil disturbance |
| Open-chamber | several weeks<br>Point or continuous measurements | <1 $m^2$ | $CH_4$ &$CO_2$:<br>slow-response IRGA | setup for diurnal cycle<br>treatment studies on small plots<br>environment similar to the ambient one can be created during flux measurement | initial soil disturbance<br>need upstream and downstream chamber GHG analysis<br>sensitive to pressure deficit inside the chamber<br>boundary-layer conductance affected<br>insulation required<br>more expensive |
| Closed-chamber | several weeks<br>Point measurements | <1 $m^2$ | $CH_4$ &$CO_2$: GC-FID<br>slow-response IRGA $N_2O$: GC-ECD | inexpensive<br>treatment studies on small plots<br>can measure very small flux<br>no or low electrical supply required | initial soil disturbance<br>boundary-layer conductance affected<br>insulation required<br>labour intensive |

Table 1b: Comparison of measuring techniques to determine methane flux: b) large-scale measuring systems.

| Measuring technique | Time | Space | Analyser | Advantage | Disadvantage |
|---|---|---|---|---|---|
| Tower-based eddy-covariance | continuous flux measurement flux averaged from 30 to 120 min extensive period except calm night and heavy rain | $10^2$-$10^5$ $m^2$ | $CH_4$ &$N_2O$: fast-response TDL[x] $CO_2$: fast-response IRGA | most direct approach minimum disturbance | large fetch, expensive |
| Tower-based relaxed eddy-accumulation | | | $CH_4$ &$N_2O$: TDL GC-FID or GC-ECD $CO_2$: IRGA | more stable measurement for small fluxes | large fetch, expensive when a TDL is used |
| Tower-based aerodynamic-gradient | | | | can be adapted for small plots | uncertainty on eddy diffusivity coefficient |
| Aircraft/tethered blimp for boundary-layer budget | point measurement | 0.02[w]-200 $km^2$ | TDL | measurements at regional scale. | Require manpower. Presence at night or |
| aircraft-based eddy-covariance | point measurement | 0.02[w]-200 $km^2$ | fast-response TDL | direct measurements at regional scale flux over different ecosystems on similar periods | very large fetch, ~5 times more expensive than tower-based approach no diurnal cycle daylight measurements |
| aircraft-based relaxed eddy-accumulation | | | $CH_4$ &$N_2O$: TDL GC-FID or GC-ECD $CO_2$: IRGA | | |

[z]GC-FID: gas chromatograph equipped with a flame ionisation detector .
[z]GC-ECD: gas chromatograph equipped with a electron capture detector
[y]IRGA:infrared gas analyser.
[x]TDL: tunable diode laser.
[w] repeated path over same area.

**Figure Captions**

**Fig. 1** Carbon sources from human activities = 7.1 Pt $y^{-1}$. Missing carbon sink = 1.8 Pt $y^{-1}$ (Kaiser and Schmidt, 1998)

**Fig. 2** Tracer technique for measuring methane emissions from livestock and manure (Adapted from Kaharabata, 1998).

**Fig. 3** Mass balance method for measuring GHG fluxes during grazing (adapted from Denmead et al., 1998)

**Fig. 4** Temporal and spatial scale ranges for agroecosystems and atmospheric systems (Cihlar *et al.*, 1993)

**Fig. 5** Temporal and spatial scale ranges for measurement techniques

**Fig. 6** Boundary-layer characteristics (adapted from Stull, 1998)

**Fig. 7** The global Fluxnet project will feature towers tracking the movement of carbon dioxide between various ecosystems and the atmosphere (Kaiser, 1998).

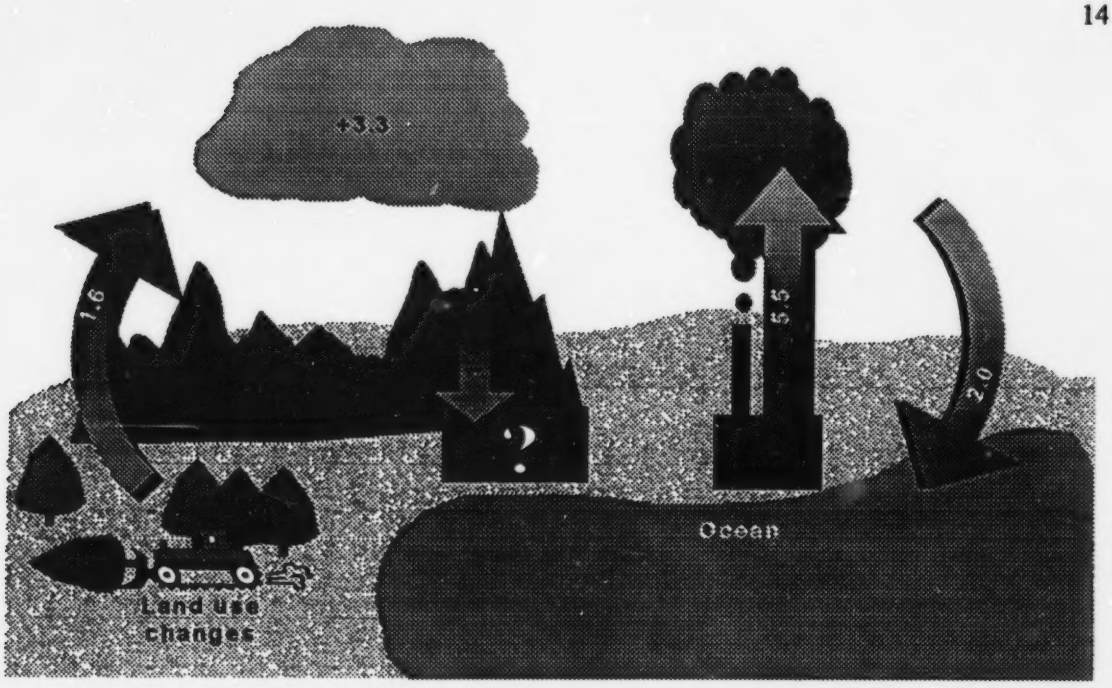



**Fig. 1** Carbon sources from human activities = 7.1 Pt $y^{-1}$. Missing carbon sink = 1.8 Pt $y^{-1}$ (Kaiser and Schmidt, 1998)

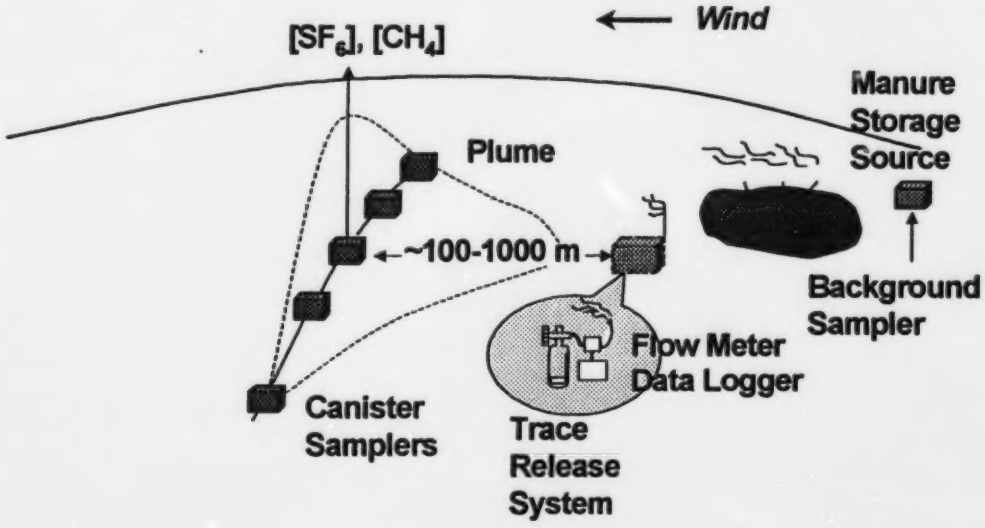



**Fig. 2** Tracer technique for measuring methane emissions from livestock and manure (Adapted from Kaharabata, 1998)

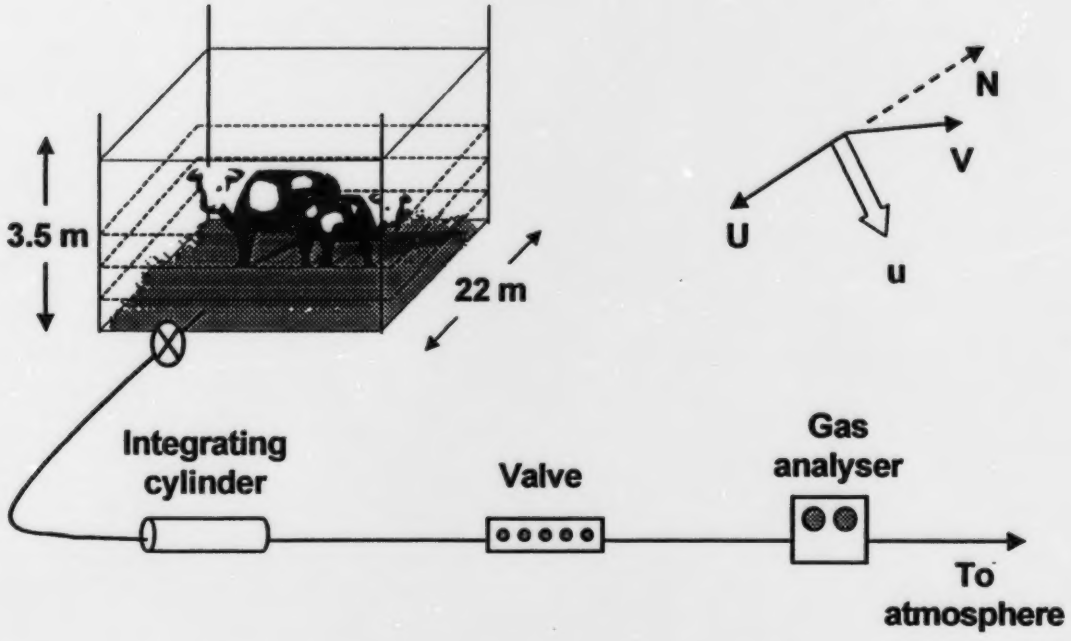



**Fig. 3** Mass balance method for measuring GHG fluxes during grazing (adapted from Denmead *et al.*, 1998)

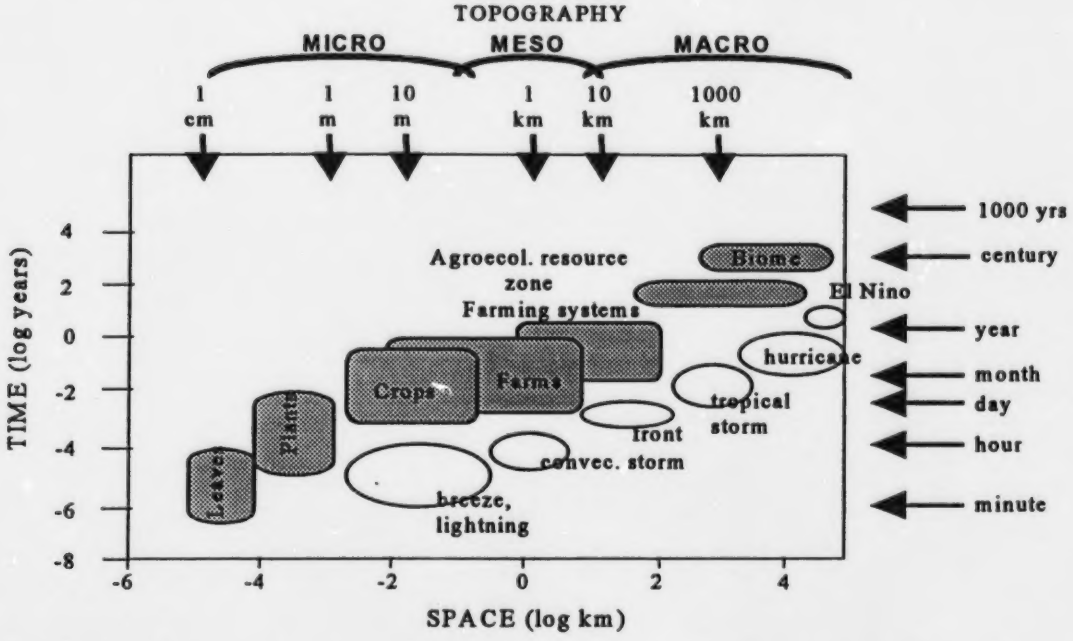



**Fig. 4** Temporal and spatial scale ranges for agroecosystems and atmospheric systems (Cihlar *et al.*, 1993)

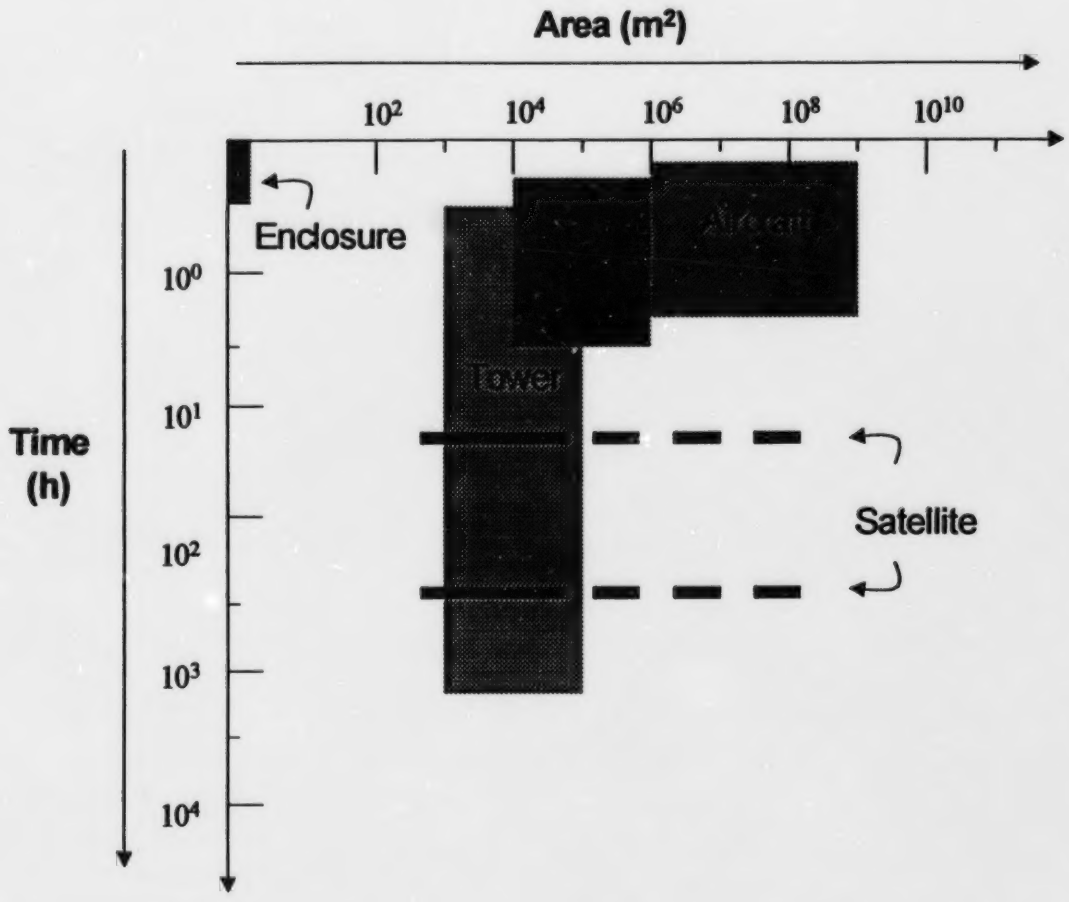
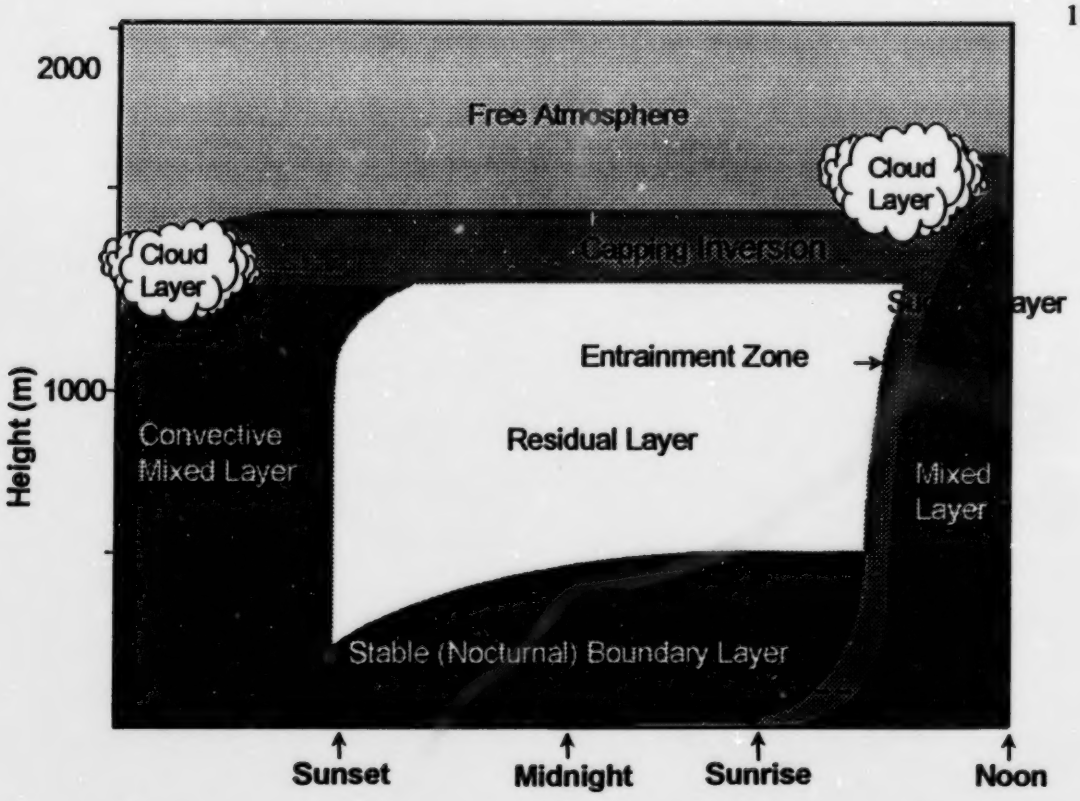



**Fig. 5** Temporal and spatial scale ranges for measurement techniques.

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